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S.C. 111/185
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Measurements of the flux of long wave radiation in the upper air 1953-54

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As part of the programme of the M.R.C. and of the Gassiot Committee of the Royal Society a new radiometer has been made suitable for use from an aircraft, and measurements of the upward and downward flux of long wave radiation have been made at levels up to 40,000 ft. in night flights during the period 1953-54. It was necessary to fly at night as the radiometer used is also partly sensitive to short wave (solar) radiation.

Instruments.

(a) Radiometer.

The radiometer used has been described by Houghton and Brewer (1954). It was designed with the present measurements specifically in mind, and the radiometers were mounted in a M.R.F. Mosquito aircraft at places indicated in the photograph (Fig. 1(a)). For the later flights two radiometers using windows of different sizes and of different origin were mounted side by side in the upward facing position. This was done as a check on the errors involved.

The instrument indicates by a resistance measurement on a resistance bridge. This is an a.c. bridge with an electronic detector which was mounted in the cabin and the measurements were made by the meteorological observer. The different radiometers are selected in turn by a switch (Fig. 1(e)). The observation is not difficult but rather more care is needed than in the ordinary air temperature measurement by the standard balanced bridge thermometer. The temperature of the radiometer must also be measured in order to apply corrections to the radiometer readings. This was done with an auxiliary resistance thermometer and an ordinary balanced bridge indicator.

(b) Other meteorological observations.

Air temperature and humidity, upon which the radiation fluxes depend, were observed in the usual way by a standard M.O. balanced bridge thermometer and a Dobson-Brewer frost-point hygrometer. The cloud details were also noted by the observer as clouds have a very great effect on the fluxes. Normal variations in temperature and humidity which exist in the atmosphere set a serious limit to the accuracy of possible interpretation of any measurements of this kind and several flights were marred by complex cloud structures.

All observations were made at 3,000 ft. intervals.

Ozone concentrations were not measured during the flights. When the work was originally planned it was thought that this might be necessary and a simultaneous programme was undertaken by Dr. Kay to permit this.

/Dr. Kay's

Dr. Kay's results (M.R.P. 817) have, however, shown that the concentration of atmospheric ozone remains small up to levels well above 40,000 ft. and showed that simultaneous ozone measurements would not be necessary. We were glad to take advantage of this simplification of flight procedure.

The flights.

In addition to a preliminary flight in a Hastings aircraft nine ascents were made in the Mosquito aircraft. The nine ascents are listed in Table 1 which gives a brief statement of the results obtained from each flight. The results of ascent 8 are given graphically in Fig. 2.

It will be seen that teething troubles continued till ascent 6 and to some extent reduced the value of results up to that stage. Ascents 2 and 5 reached unusually cold tropopauses and in each case two of the rubber sealing rings in the radiometers froze and air leaked in. For ascent 6 silicone rubber sealing rings were used. These certainly remained soft down to low temperatures but appeared to be porous, for after the flight some air was found to have leaked into the radiometer. For later flights we reverted to standard rings without any further trouble as such low temperatures were not encountered.

The results.

The flux of radiation being a very complex function of the atmospheric structure the results can most simply be described by comparison with the flux which would be calculated using one of the standard radiation charts. "Elsasser's" chart is that described by him in his paper, Elsasser (1942), and "Yamamoto's" chart is described in Yamamoto (1952). Elsasser's chart makes no provision for the diminishing path length of CO_2 with height, but this becomes important at high levels. For this reason, above 1 Km. the CO_2 radiation has always been calculated according to Yamamoto's chart. It will be noted that for the purposes of comparison of observed and computed fluxes, we had the advantage not enjoyed by any other workers of having a simultaneous frost-point hygrometer ascent.

(a) The downward flux of radiation at low levels.

Below about 1 Km. Elsasser's chart can be used without modification and Robinson's (1950) results can be readily checked over a rather wider range of temperature and radiation flux than he obtained. We do not observe the systematic difference between the calculated (after Elsasser) and the observed flux at the low fluxes which Robinson described. Our observed points and Robinson's curve are shown in Fig. 3.

(b) The downward flux at various levels below 30,000 ft.

We have compared the measured flux with those calculated in various ways and the best agreement over the widest range of conditions below 30,000 ft. has been obtained by using Elsasser's chart to compute the water vapour radiation but with a pressure correction directly proportional to p, Yamamoto's chart for the radiation from the carbon dioxide, and multiplying the result by 1.2 (a factor which arises, in part at least, from different allowances for overlap between the two spectral bands of water vapour and CO_2). The accuracy of the result calculated in this way will depend chiefly upon the accuracy of the humidity data. Our results are shown plotted in Fig.4 as the difference between the observed radiation and that calculated in the above way, but without the application of the factor 1.2.

The upward radiation stream.

Patches of low cloud affect the upward radiation stream at all levels above the cloud, and all ascents except Nos. 5, 8 and 9 were affected in this way. Even on these there may have been a few patches of dispersing low cloud. The various pressure effects cannot be separated for the upward stream since most of the radiation originates at low levels, but the indications are that the

/chart

chart values are too small and that areas on the chart when multiplied by about 1.2 will give substantially the correct answer.

Clouds.

Dense clouds have always appeared to have emissivities of 100%. The emissivity of visible cirrus clouds is, however, very variable. For example, a very tenuous cirrus cloud present in a very deep layer - possibly 9,000 ft.- radiated very little more than would be expected from its water vapour - the additional grey emissivity certainly being less than 10%.

The emissivity of the ground.

On five of the ascents when successful measurements of the upward radiation were made, the values observed were consistently less than that to be expected if the earth's surface were a perfect black-body. The results indicated an emissivity for the ground of 90-95%. It would be valuable to make further measurements to confirm this, and also to find its variation with type of surface; in particular, measurements on snow-cover would provide interesting results.

The divergence of the radiation fluxes.

The cooling of the atmosphere by radiation is the main meteorological interest. To the sort of accuracy we are prepared to accept, calculated and observed divergences agree. The main feature of a general cooling of the clear atmosphere of 1 or 2°C/day is clearly shown, and also its fluctuations due to varying cloud and humidity patterns. Fig. 2 shows the calculated and observed divergences plotted as cooling rates in °C/day for 3,000 ft. layers as observed in ascent 8. The intense cooling of 9°C/day of the Sc at 3,000 ft. would occur near the ground if the cloud were absent, and the moist layer at 25,000 ft. has concentrated the divergence into itself which would otherwise have been spread out more uniformly.

If attempts are made to compute non-adiabatic cooling rates for introduction as correction terms in dynamic meteorology or numerical forecasting, the main errors will be due to the difficulty of prescribing the humidity and cloud patterns, - not due to errors in radiation charts - to which the divergence is far less sensitive.

The stratosphere.

The value of the observations in the stratosphere is unfortunately less than we had hoped. Since the radiation from ozone and CO_2 in the stratosphere is known with some confidence, and since the emissivities of small quantities of water have been measured it should be possible to determine the water content of the stratosphere from the downward flux at the tropopause. We would of course measure the "spectroscopic amount of water vapour." This is the quantity which would have the observed emissivity if it were at a pressure of 1000 mb.

Our observations are, however, very weak because at low temperatures and for small amounts of water vapour the emission is in the rotation band at wavelengths beyond 25μ , and our KRS5 window is opaque beyond about 40μ . Nevertheless using Cowling's (1950) data our observations suggest a spectroscopic water vapour content for the stratosphere which is less than 10μ , with a large probable error. Any value up to say 12μ would be possible.

For comparison we have actual measurements of the water content published by Barrett, Herndon & Carter (1950), who made three ascents to 30 Km., and Murgatroyd's (1954) results are available up to 50,000 ft. These last are regarded as entirely reliable, though, of course, the height range is limited. If we use a $\sqrt{p}$ correction to the water vapour contents, which Cowling (1950) suggests is better for the small quantities of water vapour concerned, the Barrett, Herndon & Carter data give a value of 20-40μ as the spectroscopic

/amount

amount of water in the stratosphere and Murgatroyd's results suggest 1 or 2 μ -to be compared with our value which, as mentioned above, is from 0 - 12 μ .

Acknowledgements.

All the fitting of the equipment into the aircraft was done by M.R.F. ground personnel and all the flights were carried out by M.R.F. air crew and observers. We are very grateful to the Director, Meteorological Office, for permitting this work to be carried out, and for the very pleasant and willing assistance which we received from Mr. R.J. Murgatroyd and every member of the flight, without which the work would not have been possible.

References.

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Cowling, T.G., 1950, Phil. Mag., 41, 109.

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Murgatroyd, R.J., 1954, M.R.P. 877.
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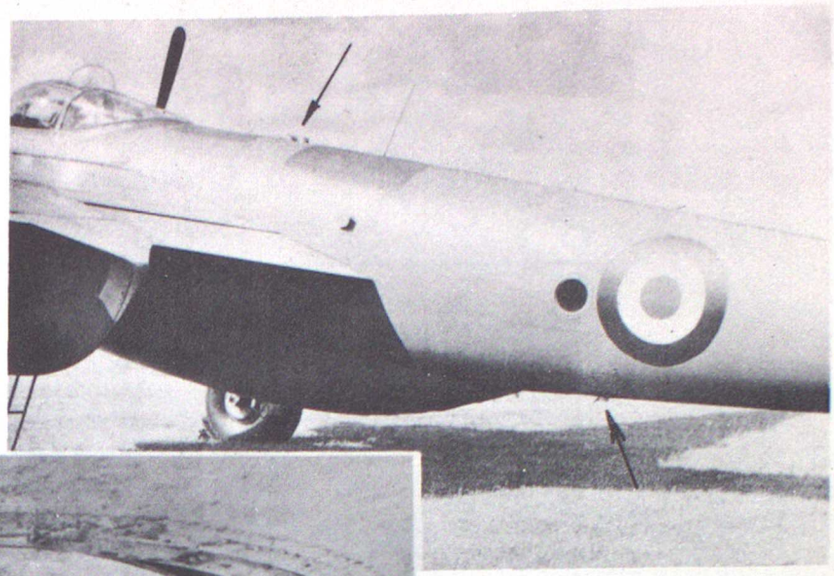
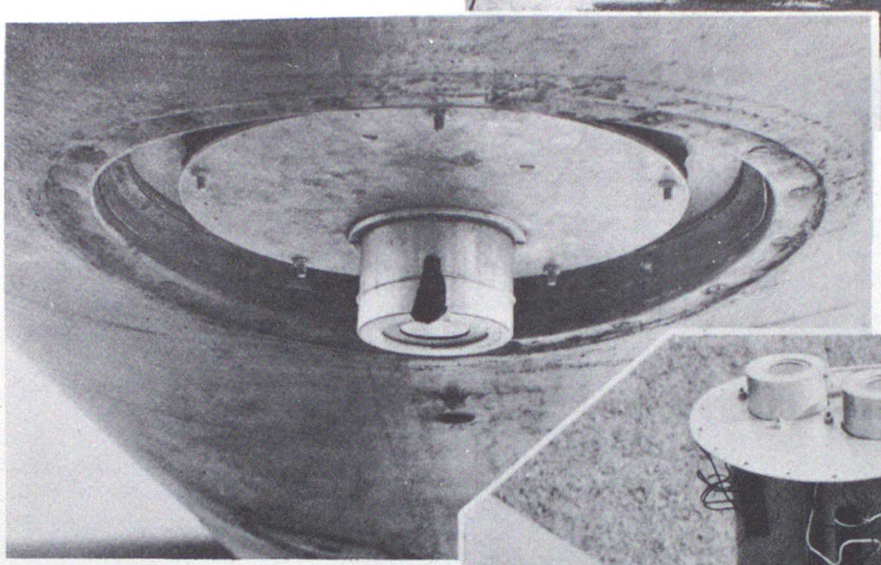
Table 1

Flights

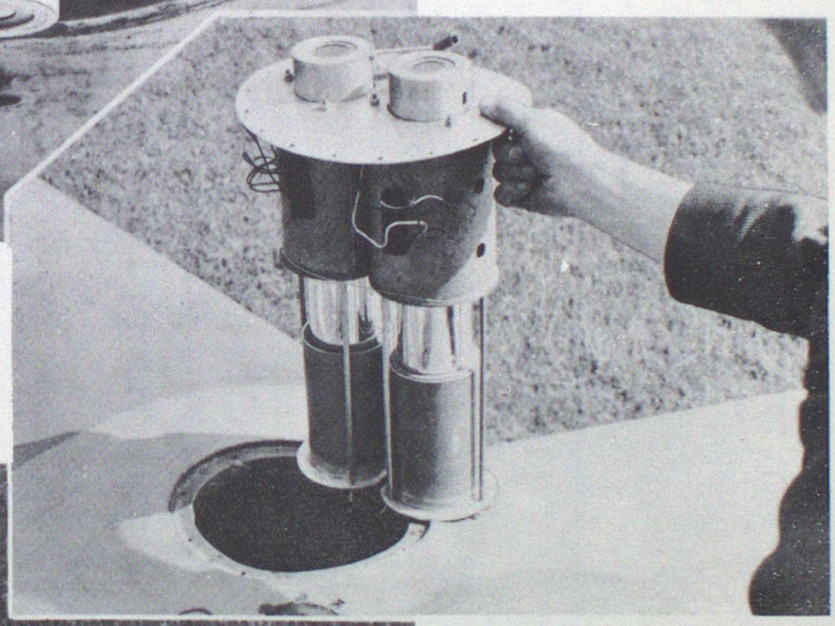
Ascent 1.	13.8.53	One upward facing radiometer only. Calibration against a black-body changed after flight.
Ascent 2.	12.8.53	4-6/8 Sc clearing during flight, some Ac and 8/8 Cs. An intermittent fault in the electronics made some readings unreliable. Air leaked into both radiometers at 36,000 ft.
Ascent 3.	23.2.54	Small patches Sc and perhaps some thin Ci at 20,000 ft. Both radiometers changed their calibration against a black-body after flight.
Ascent 4.	6.4.54	4-5/8 Sc in large patches gradually dispersing. Interpretation of the upward flux measurements above 8,000 ft. impossible on account of patchiness in the cloud. Three radiometers carried, all worked satisfactorily.
Ascent 5.	13.4.54	A few patches of Sc dispersed during flight but did not seem to affect the upward flux measurements. Two of three radiometors developed leaks at 36,000 ft. Some trouble experienced with the hygrometry.
Ascent 6.	2.7.54	Patches of Sc around 3,000 ft. dispersing during flight. Thin Ac or As 12,000 - 18,000 ft. and perhaps little Ci around 30,000 ft. One radiometer calibration did not repeat accurately after flight. One radiometer using a silicone rubber seal developed a small leak which might have affected results.
Ascent 7.	7.7.54	4/8 medium cloud present which made all readings except those at highest level difficult to interpret. All instruments worked well.
Ascent 8.	20.7.54	8/8 Sc 2,000-4,000 ft. and tr very thin Ci. All instruments worked well. This ascent is illustrated (Fig. 2).
Ascent 9.	21.7.54	Tr Sc on horizon, none over Farnborough where ascent was made. All instruments worked well.



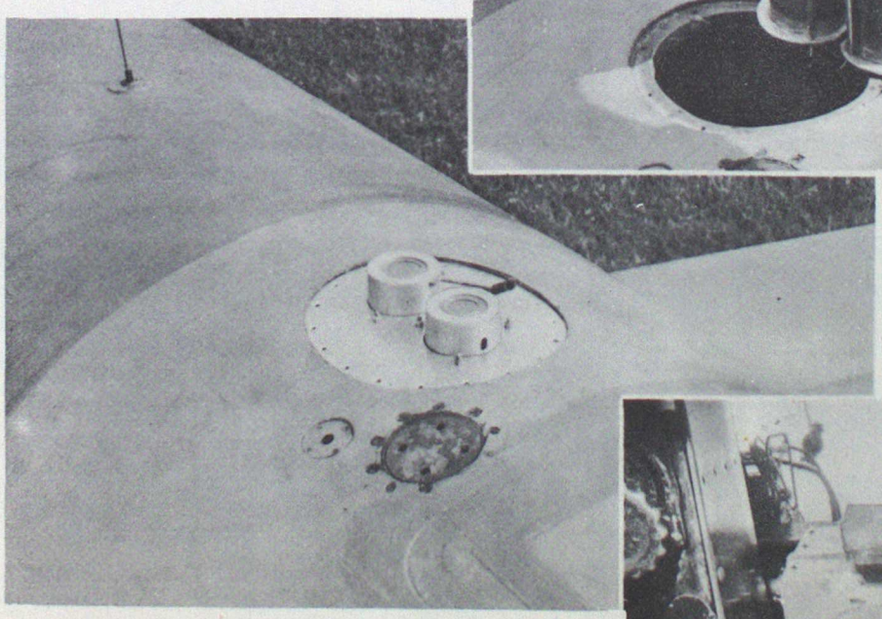
(a) MOSQUITO AIRCRAFT (POSITIONS OF RADIOMETERS INDICATED BY ARROWS



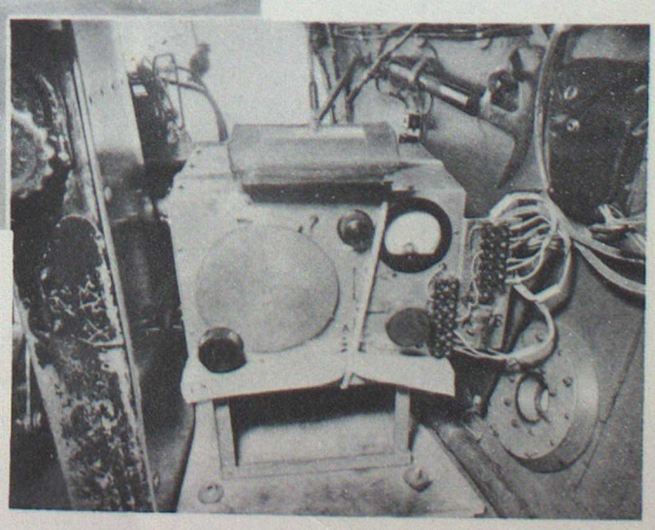
(b) DOWNWARD-FACING RADIOMETER



(c) UPWARD-FACING RADIOMETERS



(d) UPWARD-FACING RADIOMETERS



(e) MEASURING BRIDGE IN CABIN OF AIRCRAFT

FIG. I

Height in thousands of feet
0
10
20
30
40
150°
200°
250°
300°
Temperature °K.
Ascent 8.
Downward Radiation
Upward Radiation
Temperature
Frost-point
1/8 Sc.

Figure 2a

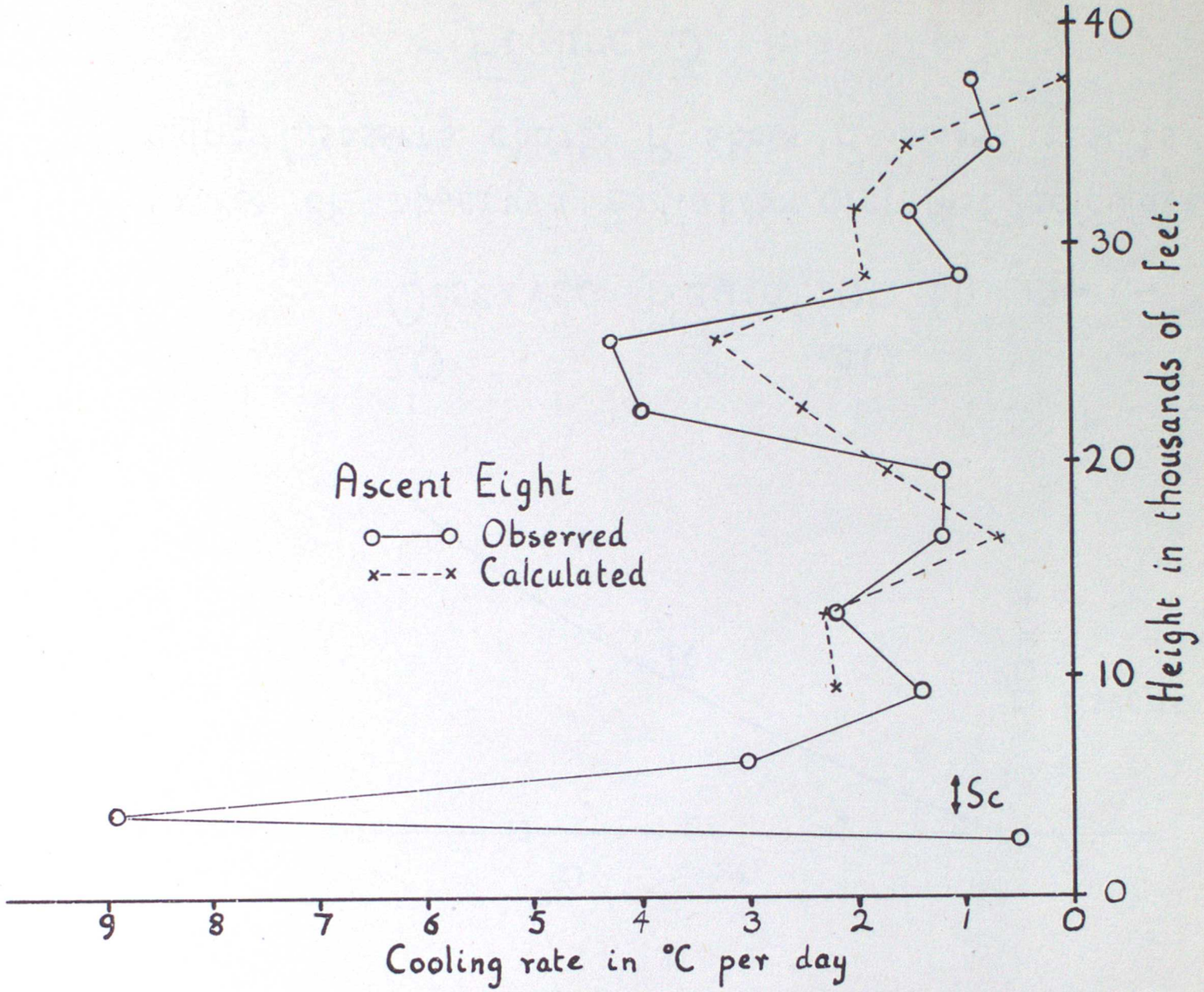

Ascent Eight
Observed
Calculated
Sc
40
30
20
10
0
Height in thousands of feet.
9
8
7
6
5
4
3
2
1
0
Cooling rate in °C per day

Figure 2 b.

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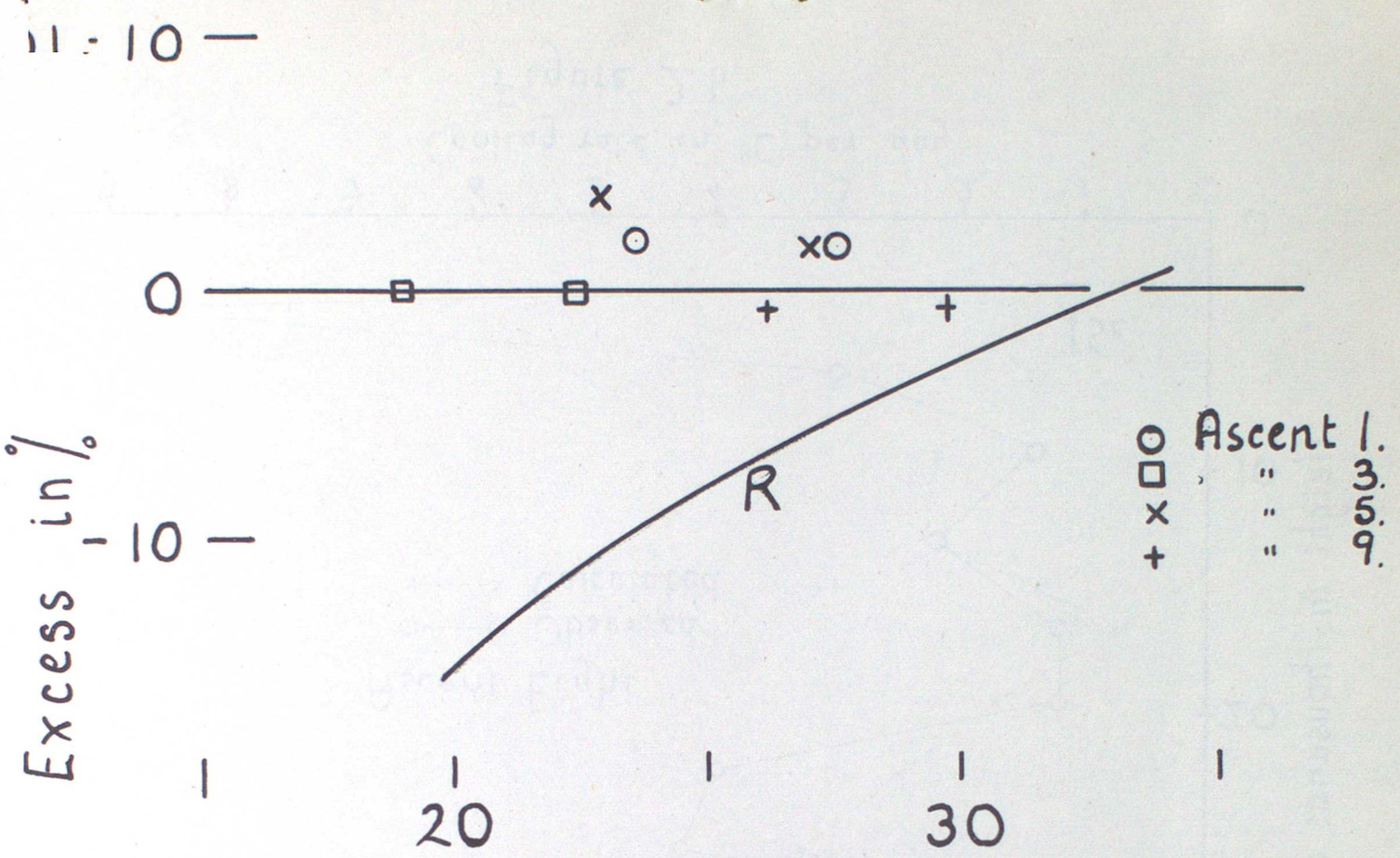

Excess of observed radiation over that calculated using Elsasser's chart. R shows Robinson's results

Figure 3.

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Figure 4